Fluoride-Salt-Cooled High-Temperature Reactors for Power and Process Heat

Nuclear Energy University Programs (NEUP)
Integrated Research Project of MIT, UCB, and UW

Charles Forsberg

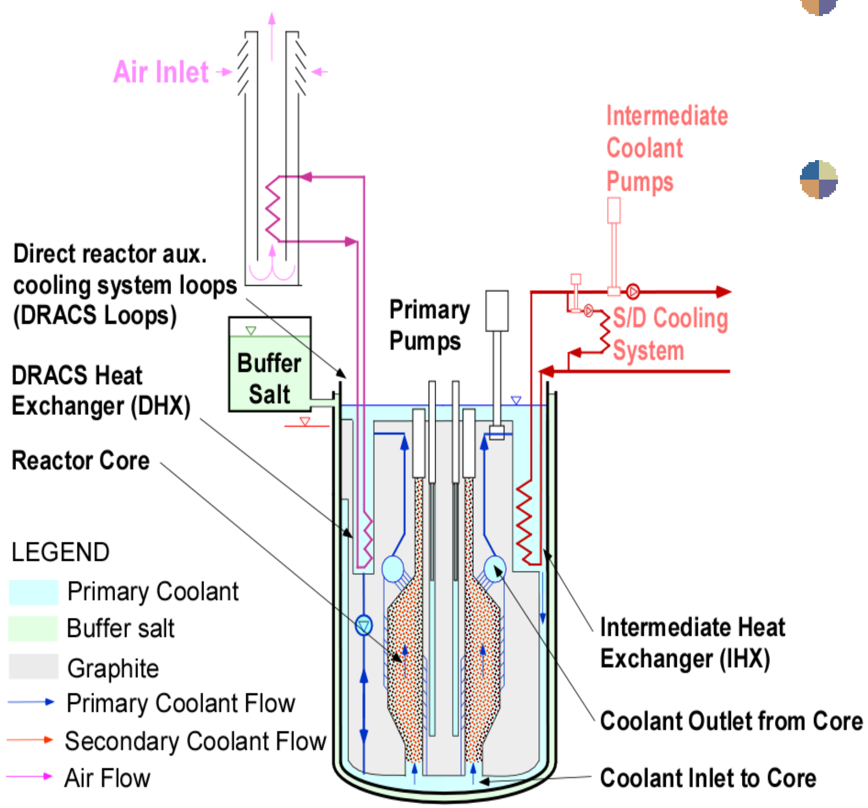
Lin-wen Hu (MIT), Per F. Peterson (UCB), and Todd Allen (UW)

Department of Nuclear Science and Engineering; Massachusetts Institute of Technology
77 Massachusetts Ave; Bld. 42-207a; Cambridge, MA 02139
Tel: (617) 324-4010; Email: cforsber@mit.edu; http://web.mit.edu/nse/people/research/forsberg.html

U.S. Department of Energy
March 20, 2012

Goals

Fluoride Salt-Cooled High-Temperature Reactor (FHR) Project



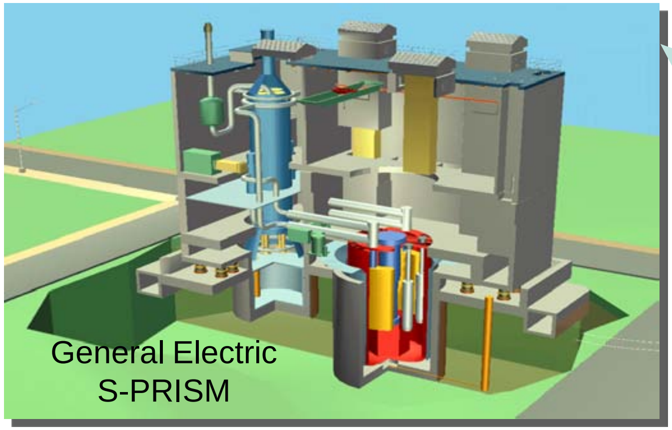
- Develop a path forward to a commercially viable FHR
- Goals
  - Superior economics (30% less expensive than LWR)
  - Limit severe accidents
  - 700°C for higher thermal efficiency and process heat
  - Better non-proliferation and waste characteristics
- Westinghouse advisory role
- Start January 2012

Fluoride-Salt-Cooled High-Temperature Reactor

Initial Base-Line Design for University Integrated Research Project

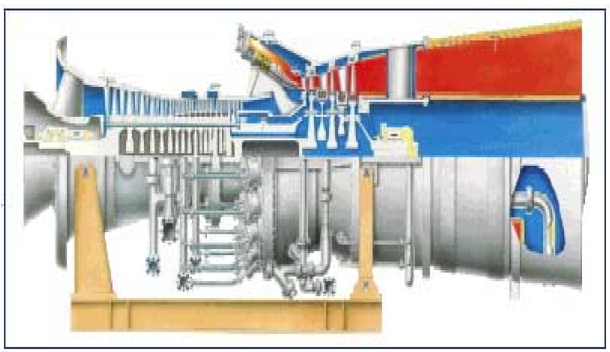
New Reactor Combines Old Technologies

Fluoride Salt-Cooled High-Temperature Reactor (FHR)



General Electric S-PRISM

Passively-Safe Pool-Type Reactor



GE Power Systems MS7001FB

Brayton Power Cycles

High-Temperature Coated-Particle Fuel

High-Temp., Low-Pressure Liquid-Salt Coolant

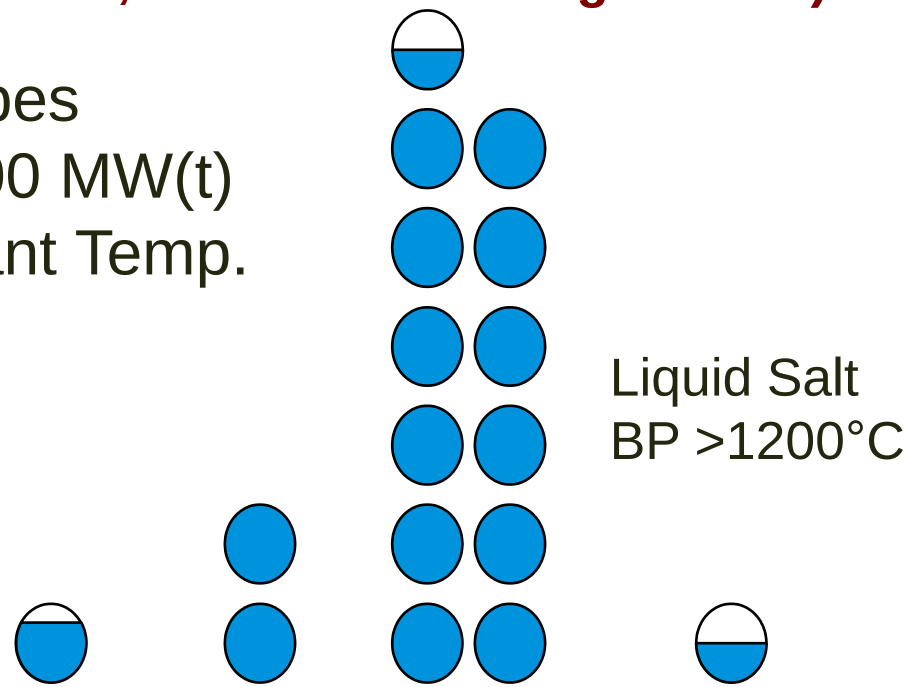
(Transparent)

Salt Coolant Properties Can Reduce Equipment Size and Thus Costs

(Determine Pipe, Valve, and Heat Exchanger Sizes)

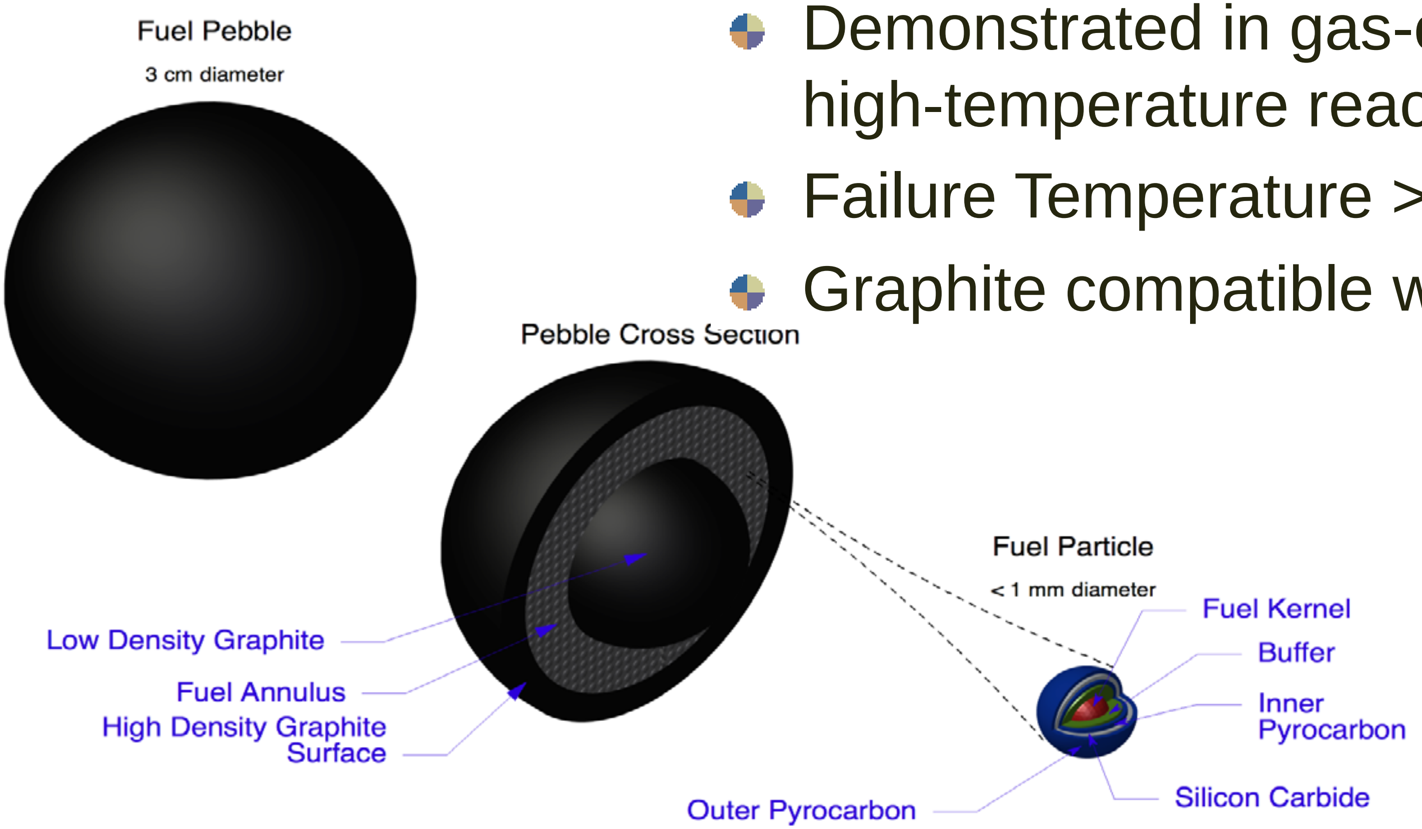
Number of 1-m-diam. Pipes Needed to Transport 1000 MW(t) with 100ºC Rise in Coolant Temp.

Baseline salt: Flibe



	Water (PWR)	Sodium (LMR)	Helium	**Liquid Salt**
Pressure (MPa)	15.5	0.69	7.07	**0.69**
Outlet Temp (ºC)	320	540	1000	**1000**
Coolant Velocity (m/s)	6	6	75	**6**

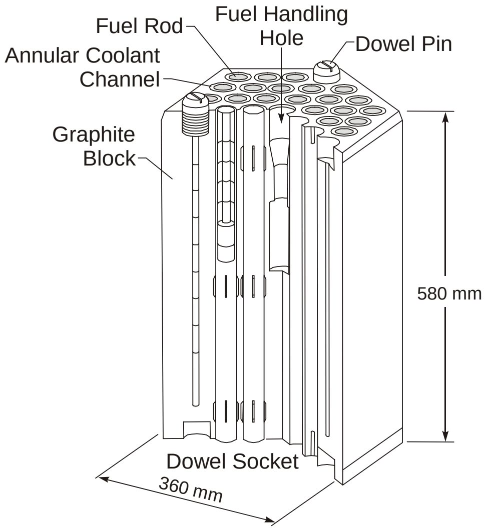
FHR Uses Graphite-Matrix Coated-Particle Fuel



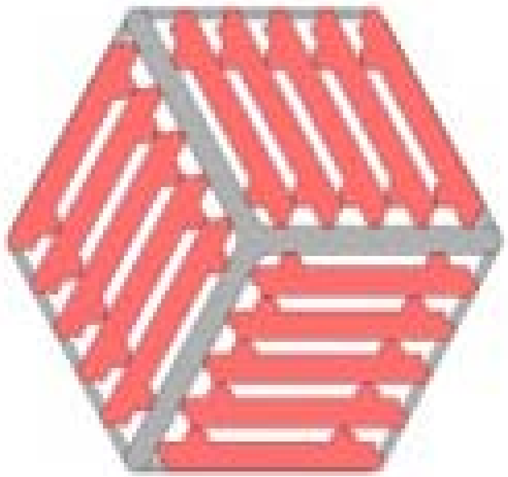
- Demonstrated in gas-cooled high-temperature reactors
- Failure Temperature >1600°C
- Graphite compatible with Salt

Liquid Coolant Enables Increasing Core Power Density by 4 to 10

Graphite-Matrix Coated-Particle Fuel Can Take Many Forms

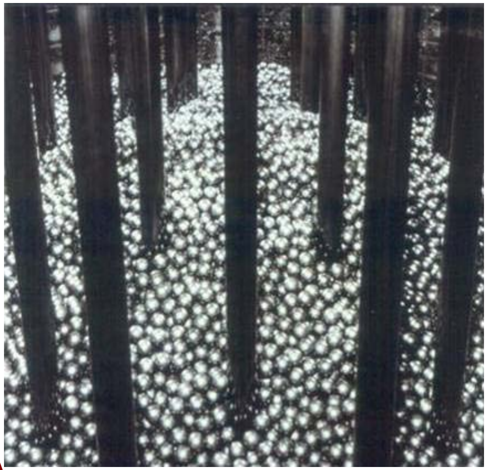


Prismatic Fuel Block



Flat Fuel Plates in Hex Configuration

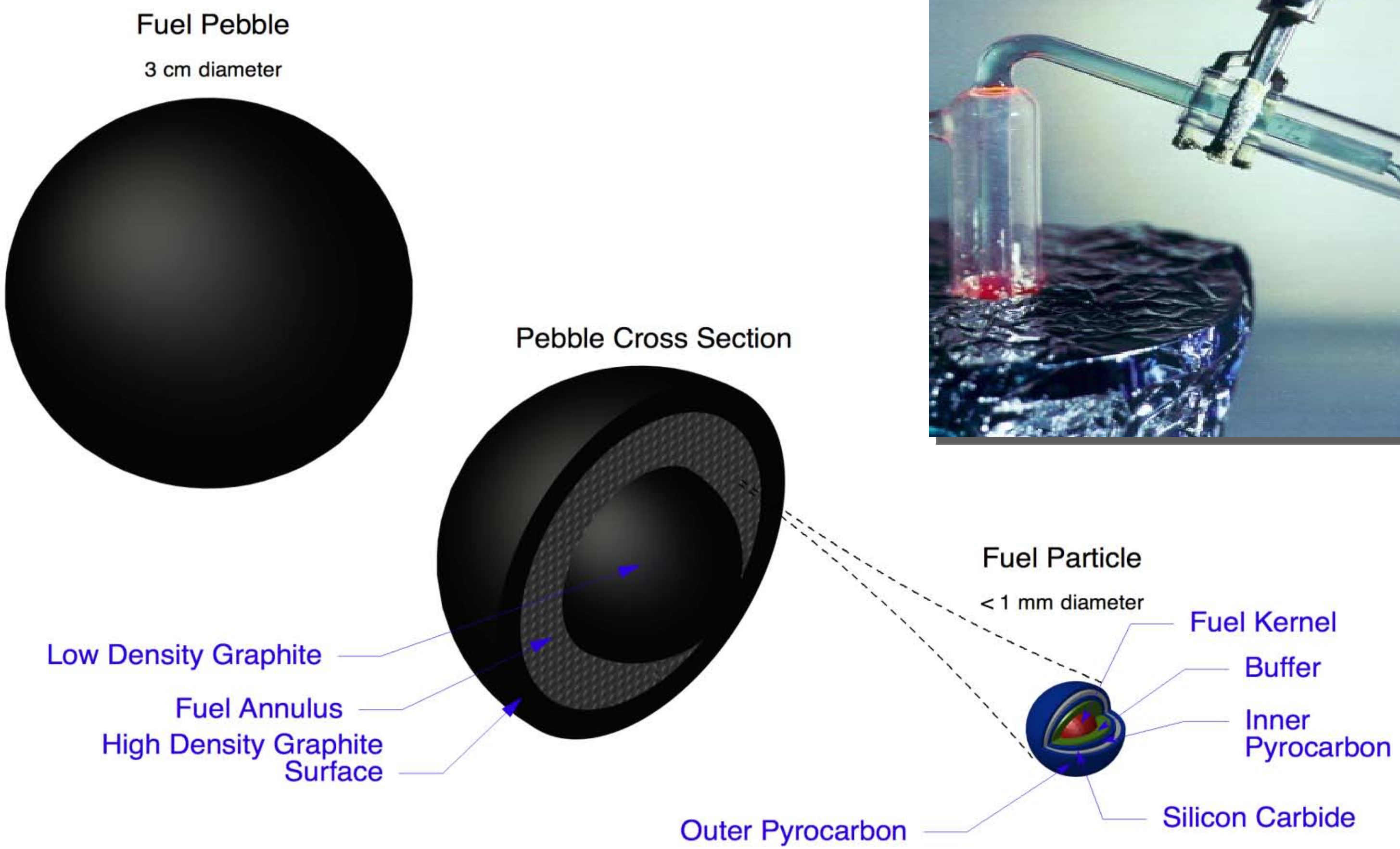
Base Case

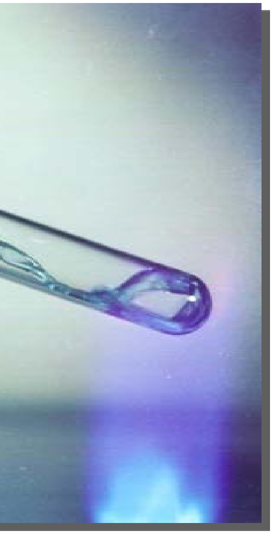


Pebble Bed

- Pebble bed
  - Lower cost
  - Easier refueling
- FHR smaller pebbles (3 cm) and higher power density

Salt Density Is Greater Than Fuel Density

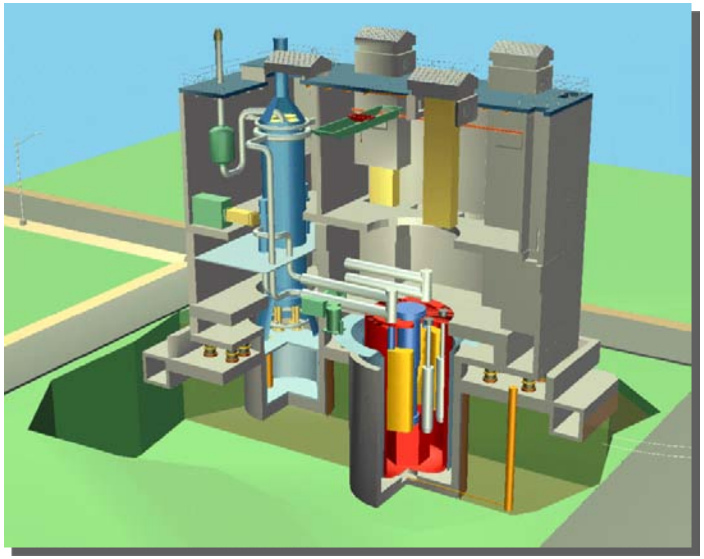




Fuel Floats

FHR Decay-Heat Safety Systems Similar to Liquid-Metal Fast Reactor

- FHR is a liquid-cooled low-pressure reactor—like liquid metal fast reactors
  - Similar layout to liquid metal reactor
  - Many safety systems from sodium fast reactors
- FHR is a high-temperature reactor
  - Modified gas-cooled reactor fuel—higher power density
  - Very high temperature fuel

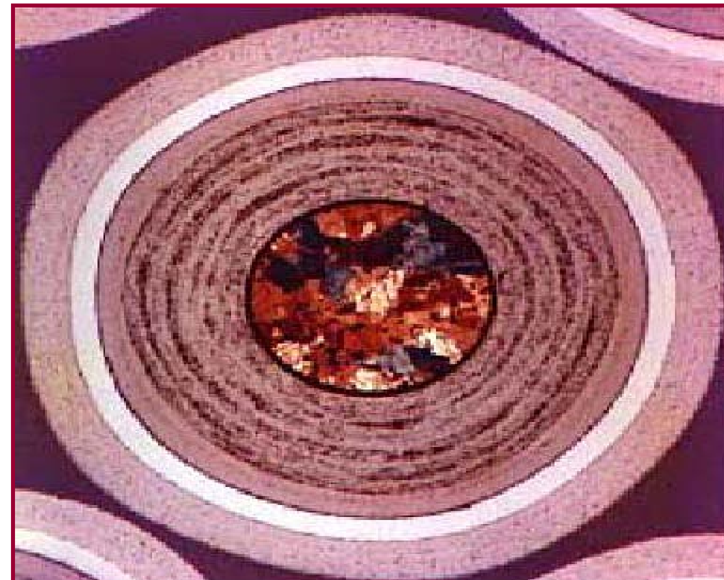


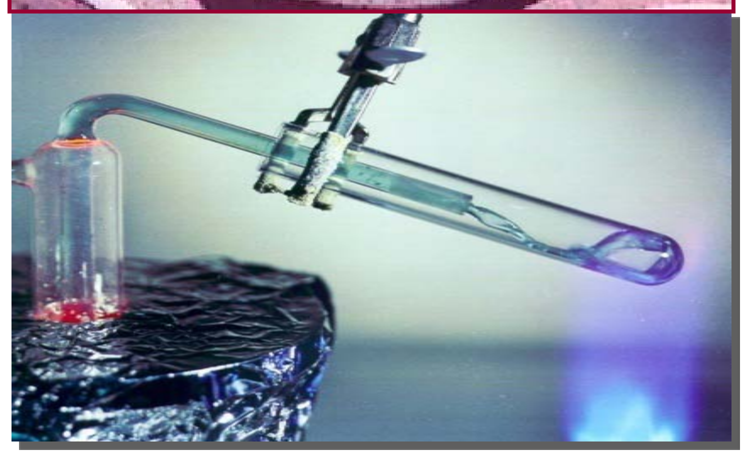
General Electric

S-PRISM

High-Temperature Fuel and Coolant Alters Safety Limits

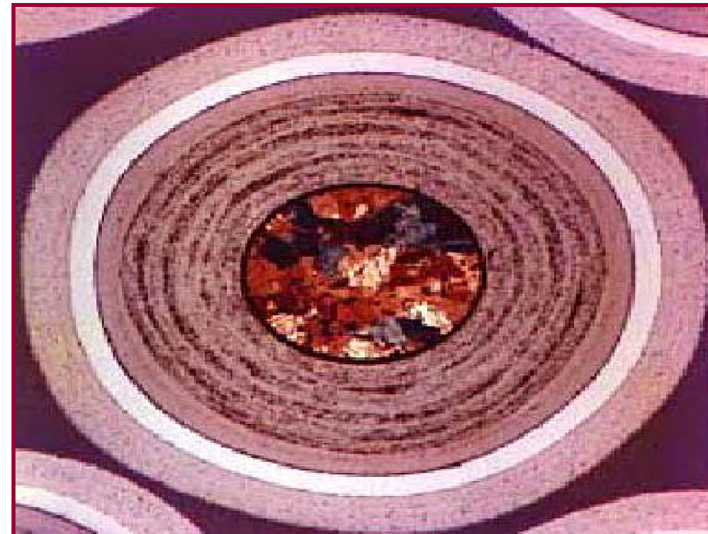
- Safety limit LWR: fuel clad failure from high temp.
- Safety limit SFR: void coefficient from boiling coolant
- Safety limit HTGR: high-temperature fuel failure
- FHR limits not well defined
  - Metal component failure
  - Bulk temperature limit

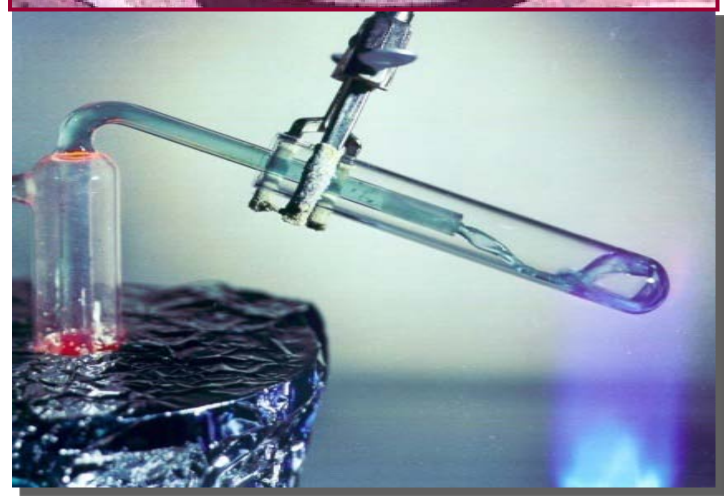




Accidents May Not Damage Core

- Fuel failure ~1650°C
  - Iron melts at 1535°C
  - Nominal peak~800°C
- Coolant boiling ~1430°C
  - Nominal peak ~700°C
- Vessel: <1200°C
- Severe accident starts outside of the core
- Different than any other reactor and not well understood

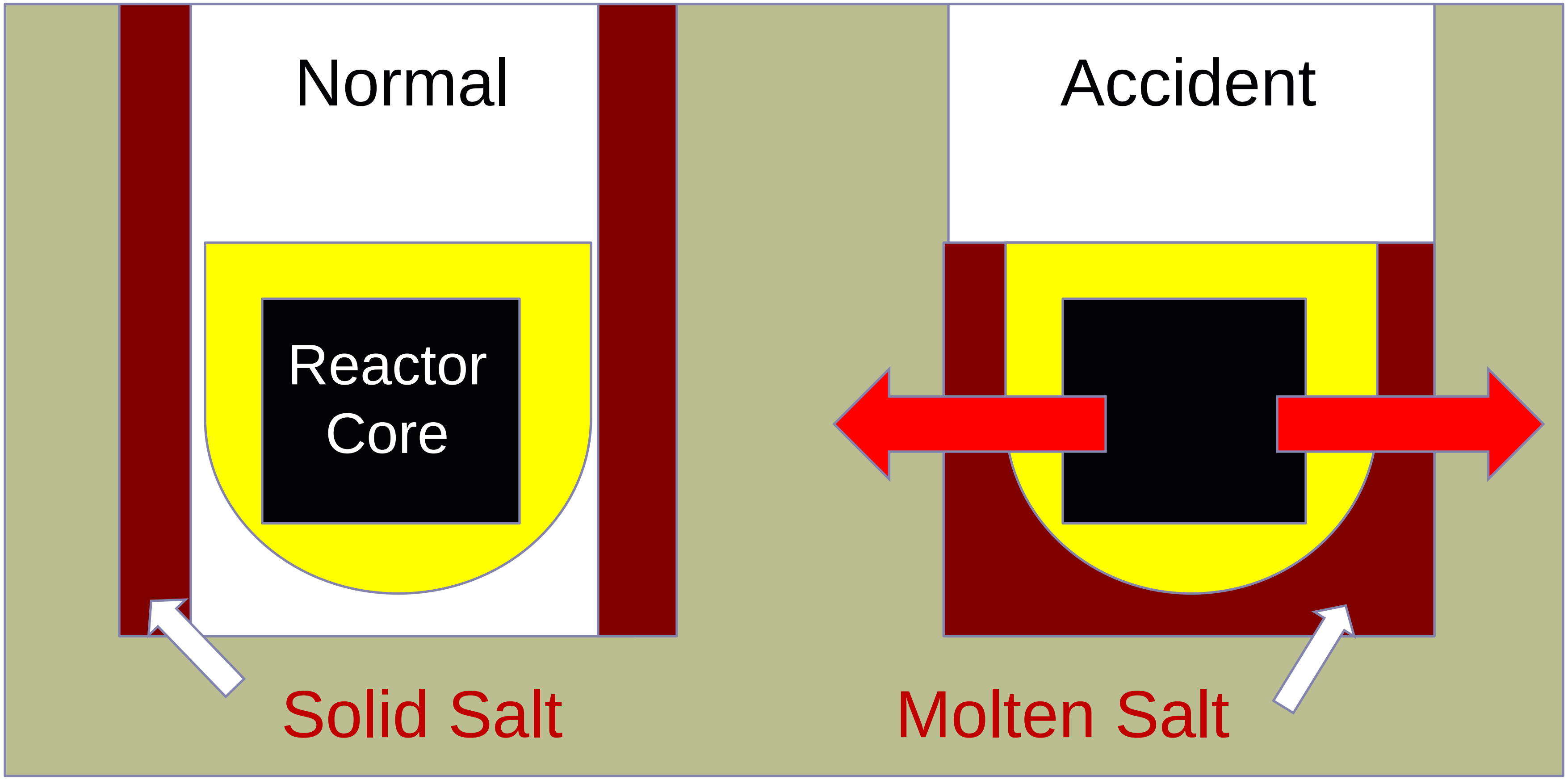




In core feedback: higher temperatures yield negative Doppler with power drop, lower salt viscosity with higher flows and T^4 radiation heat transfer

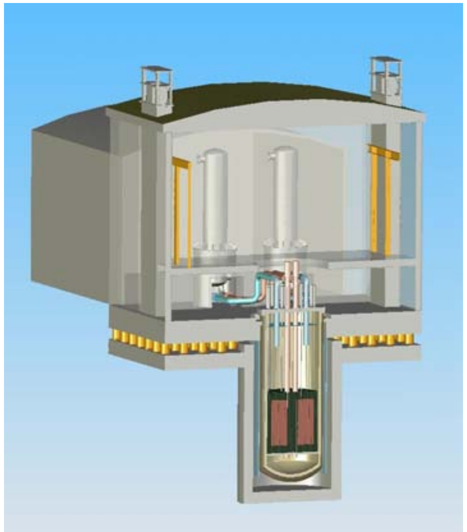
High-Temperature Capabilities May Eliminate Offsite Accident Impacts

If Fuel Is Intact, Limited Offsite Consequences



In Accident, Conduct Decay Heat to Ground Without Fuel Failure

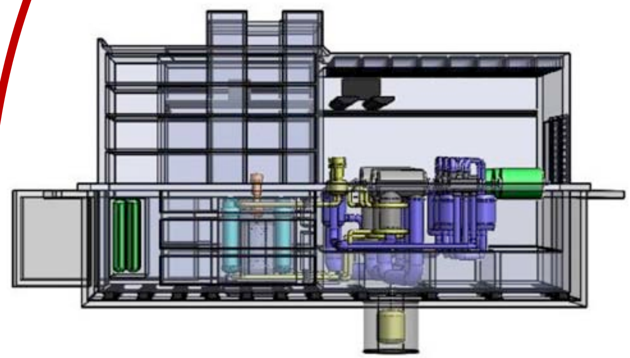
FHR Concepts Span Wide Power Range



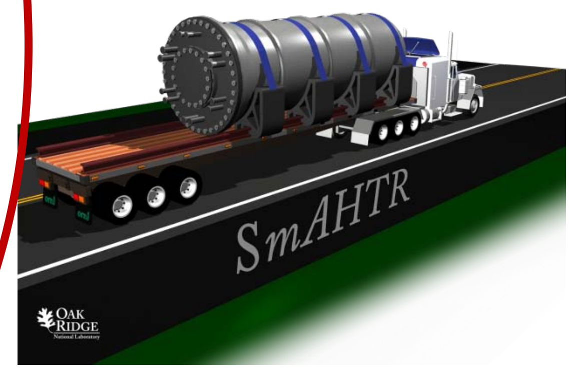
3400 MWt /
1500 MWe

OAK RIDGE
National Laboratory

Base Case



410 MWe



125 MWt/50 MWe

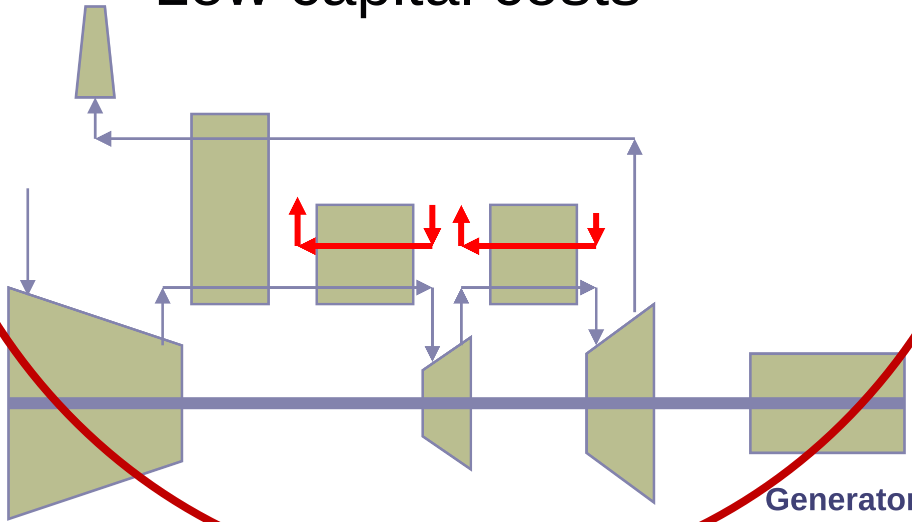
OAK RIDGE
National Laboratory

Many Options for Power Cycles

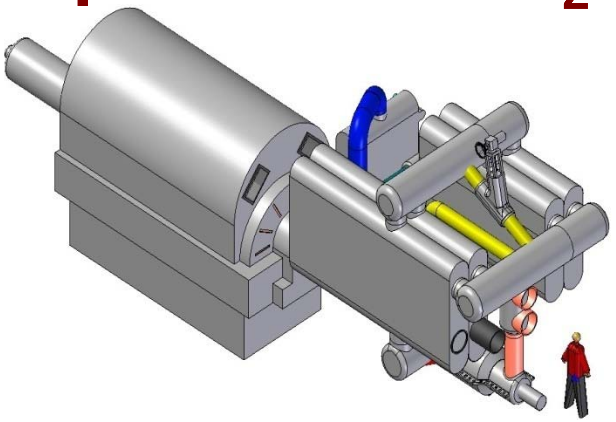
Base Case

Air Brayton Cycle

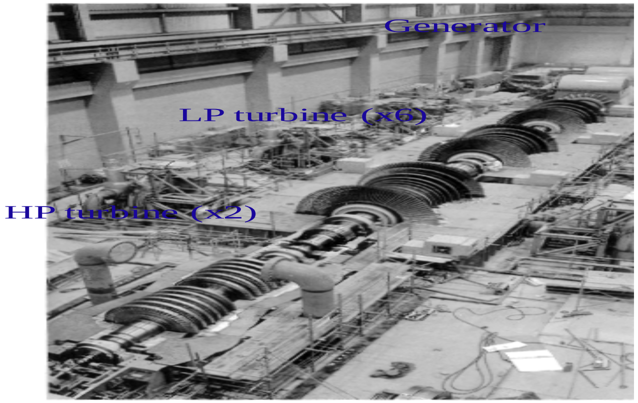
- Air Brayton cycle based on natural gas turbine
- Dry cooling
- Low capital costs



Supercritical CO_2



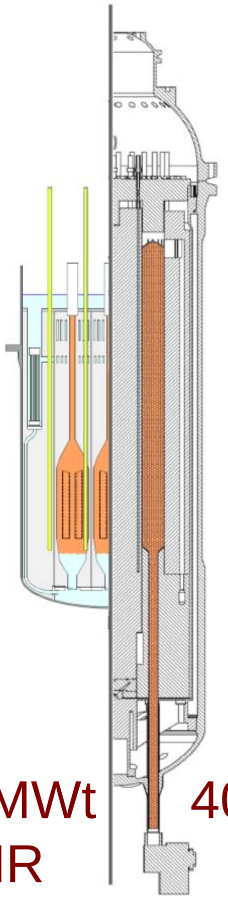
Steam



And Process Heat

Initial FHR Cost Estimates Lower than Light-Water and Gas-Cooled High-Temperature Reactors

- Lower energy costs than Advanced Light Water Reactors (LWRs)
  - Primary loop components more compact than ALWRs per MWth
  - No stored energy source requiring a large-dry containment
  - Higher plant efficiency (40 to 50%)
  - Unanswered: Does the FHR size need to approach LWRs for superior economics
- Lower construction cost than high-temperature gas-cooled reactors



University Integrated Research Project

Massachusetts Institute of Technology (Lead)
University of California at Berkeley
University of Wisconsin at Madison

Cooperation and Partnership With

United States Department of Energy

Westinghouse Electric Company

Oak Ridge National Laboratory

Idaho National Laboratory

Three Part University FHR Integrated Research Program

- Status of FHR and develop near-term path forward
- Technology Development
  - Materials development
  - In-reactor testing of materials and fuel
  - Thermal-hydraulics, safety, and licensing
- Integration of Knowledge
  - Pre-conceptual design of test reactor
  - Pre-conceptual design of commercial reactor
  - Roadmap to test reactor and pre-commercial reactor

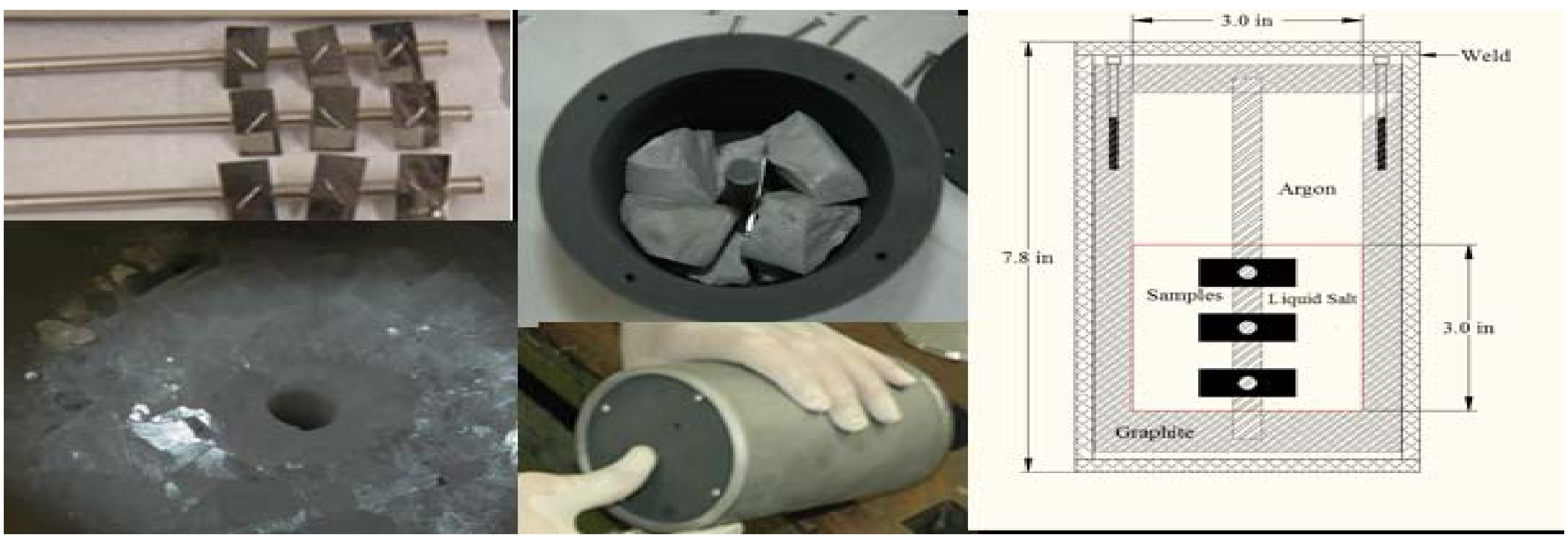
FHR Workshops to Define Current Status and Path Forward

Strategy to Drive Program, Technical, and Design Choices

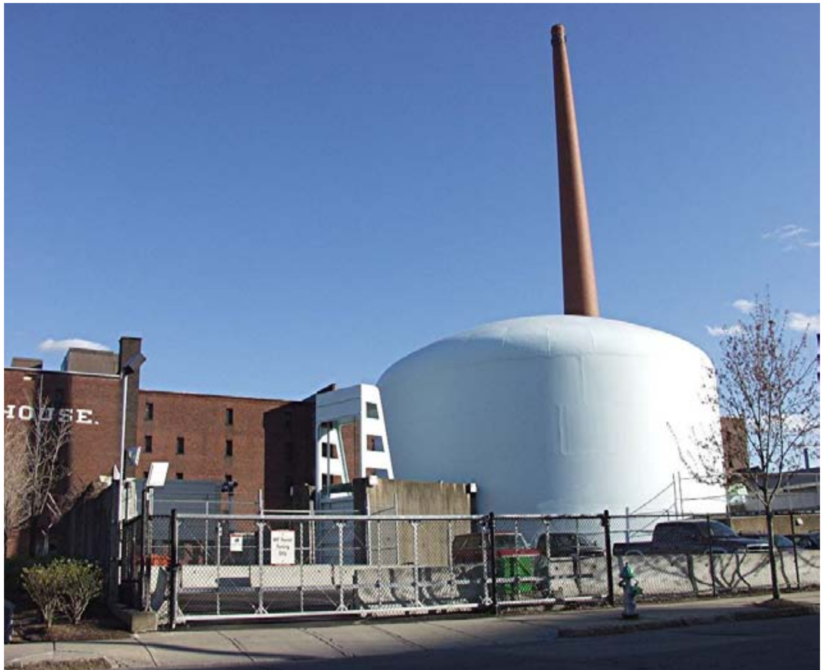
- Subsystems definition, functional requirement definition, and licensing basis event identification (UCB): Held Feb 23-24, 2012
- Methods and experiments for thermal hydraulic, neutronic, and structural analysis (UCB)
- Materials identification and component reliability phenomena identification and ranking (UW)
- Development roadmap and test reactor performance requirements (MIT)

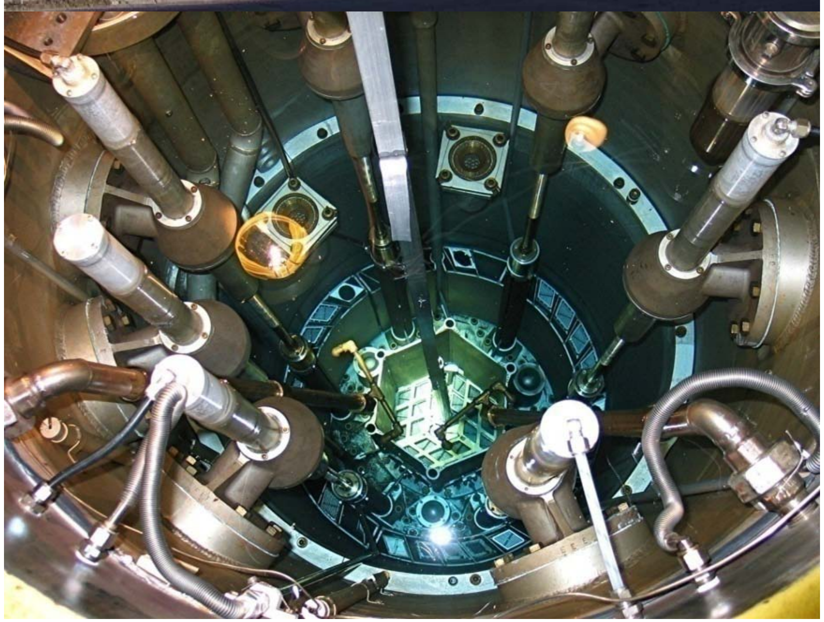
The University of Wisconsin Will Conduct Corrosion Tests

- Evaluate salts and materials of construction
- Strategies to monitor and control salt chemistry
- Support reactor irradiations



MIT To Test Materials In MIT Reactor





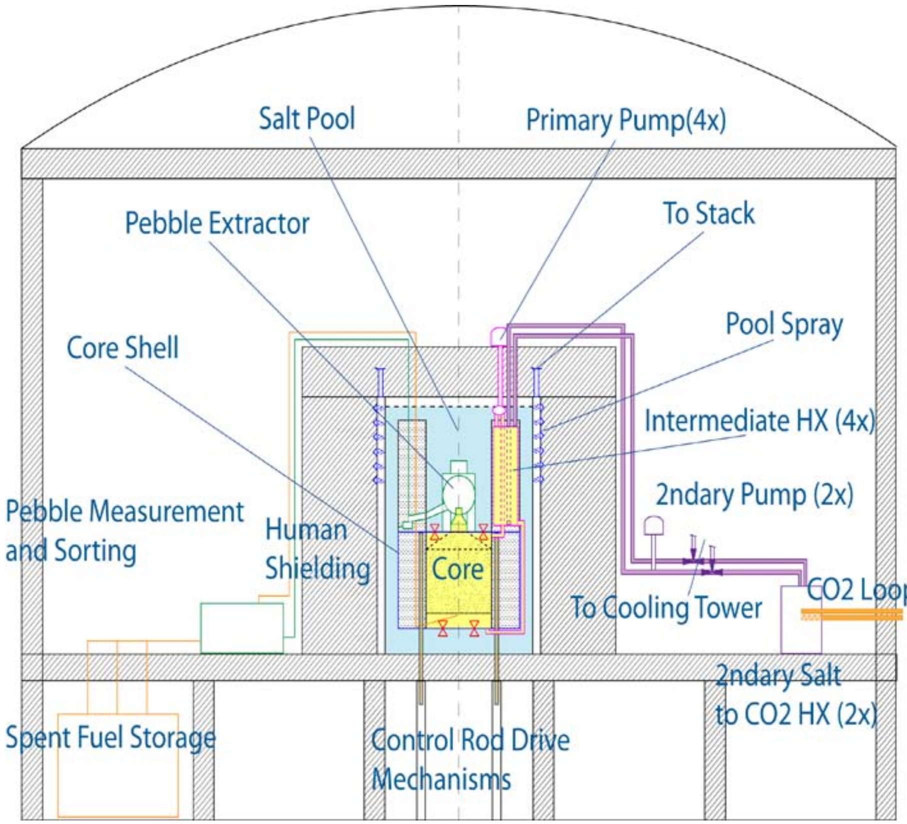
- 6-MWt water-cooled reactor
- Operates 24/7
- In core tests
  - Tests in 700°C flibe liquid salt in core
  - In-core materials, coated particle fuel (or surrogate)
  - First low-temperature safety test of salt in core completed

UCB to Conduct Thermal Hydraulics, Safety, and Licensing Tests

- Experiments using organic simulants
- Analytical models to predict thermohydraulic behavior
- Support simulation of reactor irradiation experiments

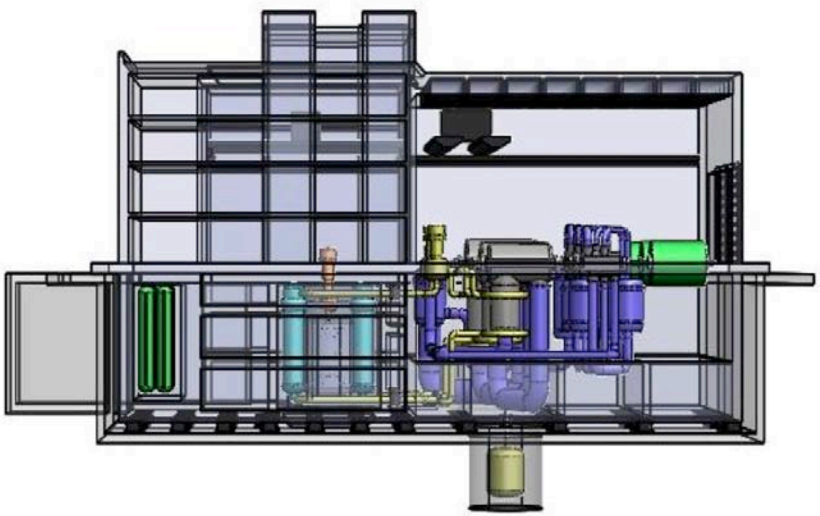
MIT To Develop Pre-Conceptual Test Reactor Design

- Identify and quantify test reactor functional requirements
- Examine alternative design options
- Develop pre-conceptual design



UCB to Develop Commercial Reactor Pre-Conceptual Design

- Identify and quantify power-reactor functional requirements
- Integrated conceptual design to flush out technical issues that may not have been identified in earlier work



MIT Leads Roadmap Development To Test Reactor and Commercial Power Reactor

- Roadmap to power / process heat reactor
- Identify and scope what is required and schedule
- Includes licensing strategy
- **Partnership with Westinghouse Electric Company**

An FHR Advisory Panel Has Been Formed

First Meeting: February 22, 2012

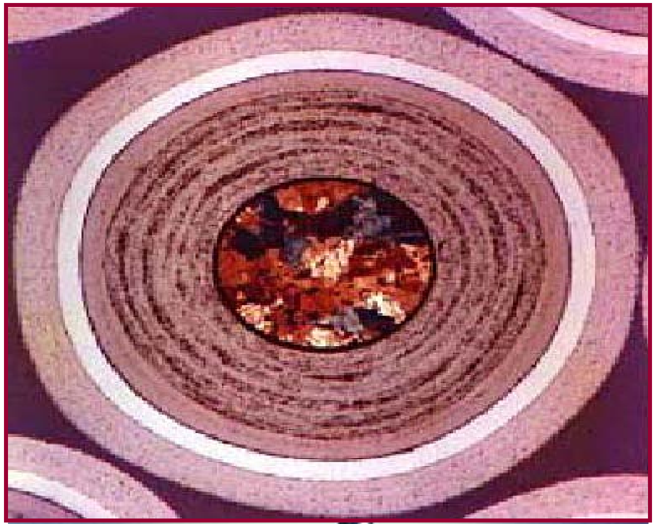
- Regis Matzie (Panel Chair): Retired senior vice president and chief technology officer of Westinghouse)
- Douglas Chapin: Previous principal at MPR and current senior consultant)
- John McGaha: Retired senior executive of Entergy Nuclear)
- Dan Mears: President and CEO of Technology Insights)
- James Rushton: Retired head of Nuclear Science and Technology division at ORNL)

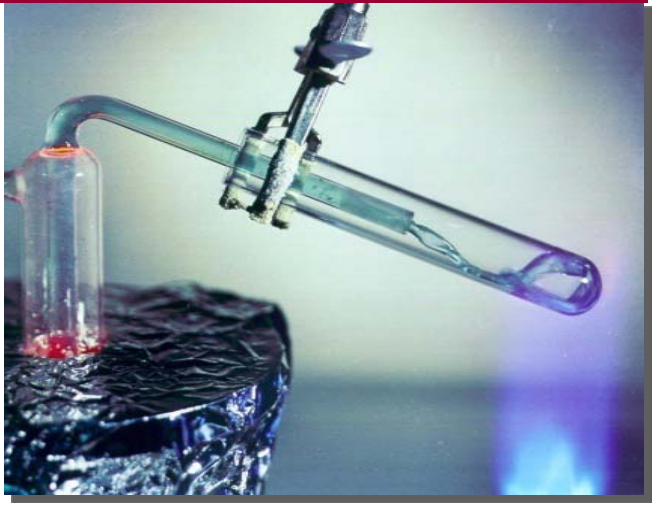
The Advisory Panel has been constituted to advise the IRP on how best to successfully complete their DOE contract in a manner that provides a viable path forward in pursuit of a commercially successful FHR.

IRP Requires Coupling with Other Programs

The FHR Foundation Includes Three Other DOE Programs

- Graphite-matrix coated-particle fuel
  - Require fuel
  - Need samples for irradiation testing
- High-temperature materials
  - Operating temperature 700ºC
  - Accident limits likely outside reactor core
- Materials codes and standards





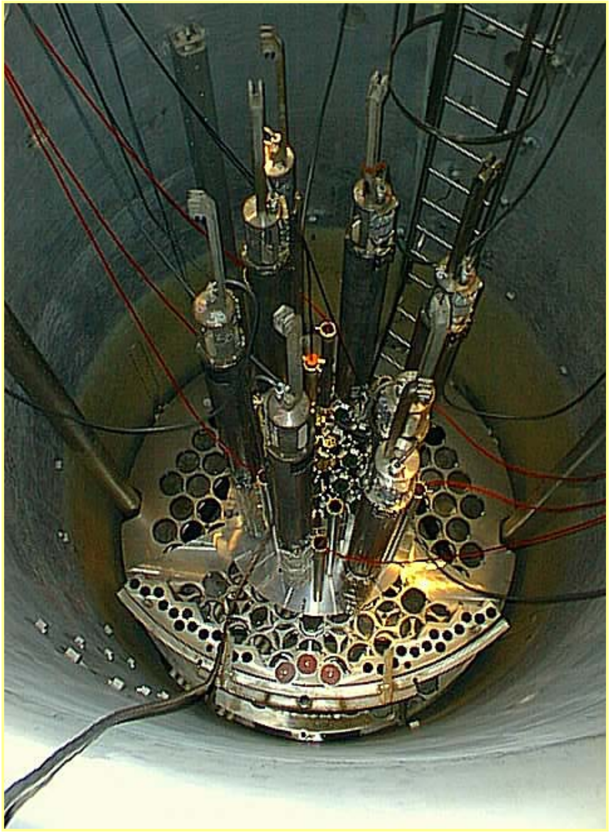
We Are Working with ORNL and INL

- ORNL
  - Supply ^{7}Li salts
  - High-temperature pebble bed salt loop
  - Other
- INL
  - Update thermal hydraulics codes
  - Tritium (fusion) program
  - Test materials

ORNL 200 kW
700°C Salt Loop

IRP Working With DOE-Czech Republic Cooperative Agreement

- Criticality tests in Czech Republic on ^{7}Li salts for FHR
- U.S. Participants at first meeting: January 2012
  - DOE
  - ORNL
  - IRP Participants
    - Prof. Forget (MIT)
    - Prof. Greenspan (UCB)



Goal to Work With Others To Meet FHR Challenges

- National Laboratories: SNL
  - Supercritical CO_2 power cycle
  - Matches temperature range of FHR (600 to 700°C)
  - Higher efficiency directly improves FHR economics
- Universities: Ohio State
  - NEUP on decay heat removal with air heat sink
  - Directly applicable to FHR
- Chinese Academy of Science
  - Agreement between DOE and CAS
  - Molten salt reactor program going to 700 people
  - Large overlap with FHR

Developing FHR Grand Challenge List

Technologies That Would Improve FHR Where Others Have Incentives to Meet Challenges

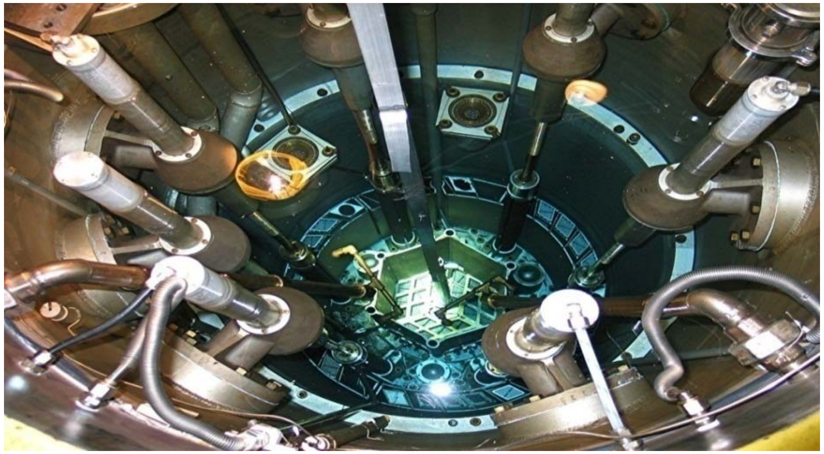
Challenge	Other Users
Tritium removal from salt	Fusion, MSR
Simulation of pebble bed core	NEAMS, China
Passive decay heat removal with low-temperature shutoff	LFR and SFR
Lithium isotopic separation	LWRs, MSR, Fusion

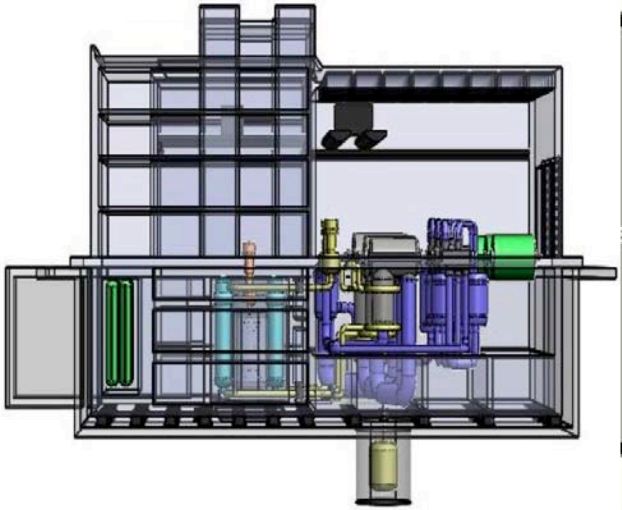
In each case have defined the challenge and possible paths forward: Goal to engage others

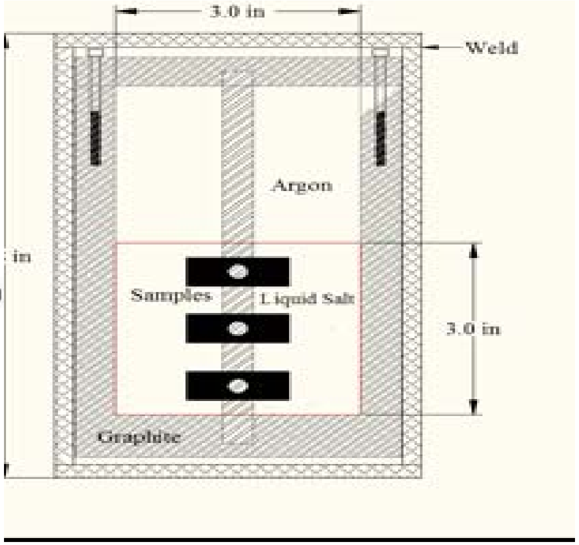
Conclusions

- Initial assessments favorable
- FHR combines existing technologies into a new reactor option—No FHR has ever been built
- January start: Today 9 graduate students on board and accelerating
- Putting together partnerships to leverage work
  - Need continued DOE programs
  - National and international partnerships

Questions







Biography: Charles Forsberg

Dr. Charles Forsberg is the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study, Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project, and University Lead for Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.

http://web.mit.edu/nse/people/research/forsberg.html

The United States Has a Competitive Advantage with FHR

- Developed and currently leads in FHR R&D
- Experience with MSR and has a working inventory of lithium-7 flibe salt
- Leads in coated-particle fuel technology because of NGNP high-temperature reactor program
- Leads in candidate FHR power systems
  - Gas turbines
  - CO_2 supercritical cycle

Base Case Salt is $^{7}Li_2BeF_4$ (Flibe)

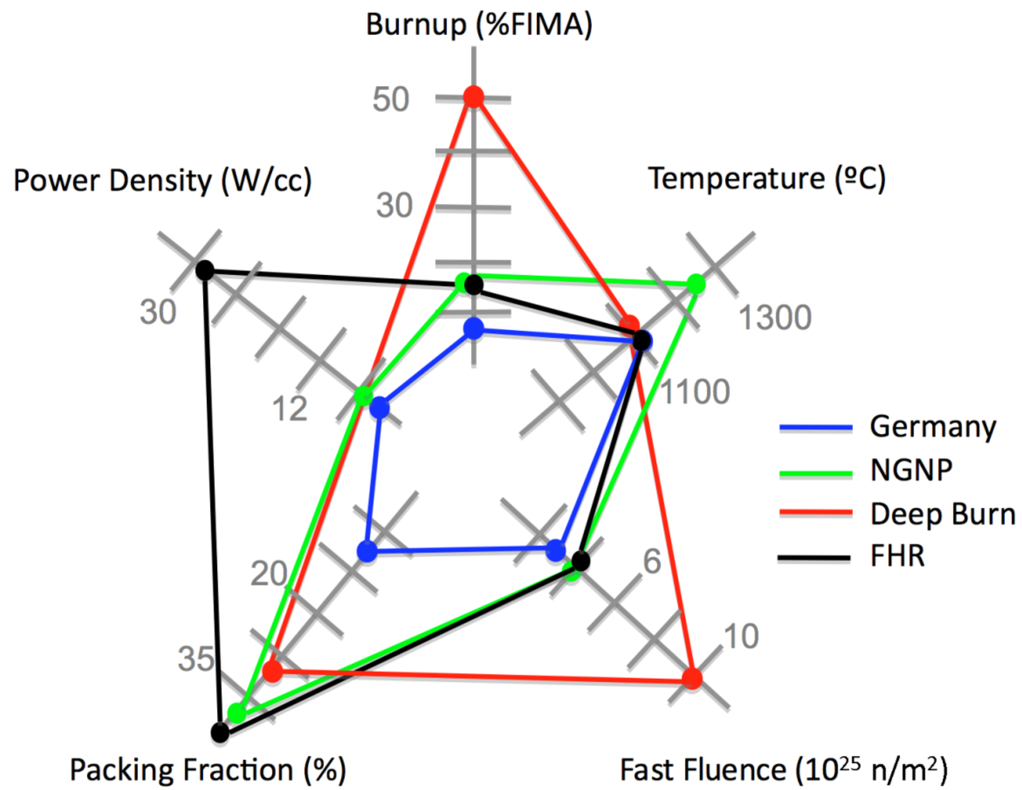
Physical Properties of Coolants

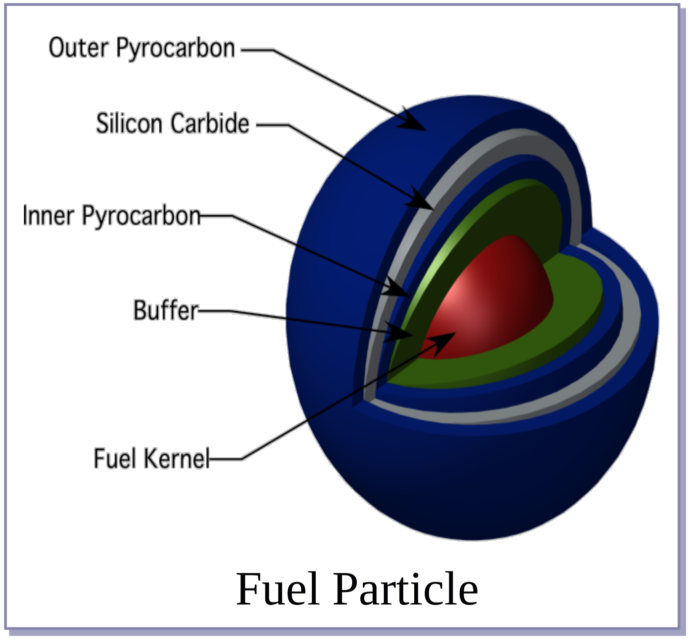
Coolant	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m^3)	C_p (kJ/kg °C)	ρC_p (kJ/m^3 °C)
Li_2BeF_4 (Flibe)	459	1430	1940	2.42	4670
59.5NaF-40.5ZrF_4	500	1290	3140	1.17	3670
26LiF-37NaF-37ZrF_4	436		2790	1.25	3500
31LiF-31NaF-38BeF_2	315	1400	2000	2.04	4080
8NaF-92$NaBF_4$	385	700	1750	1.51	2640
Water (7.5 MPa)	0	290	732	5.5	4040

Salt compositions are shown in mole percent. Salt properties at 700ºC and 1 atm. Sodium-zirconium fluoride salt conductivity is estimated—not measured. The NaF-$NaBF_4$ system must be pressurized above 700°C; however, the salt components do not decompose. Pressurized water data are shown at 290°C for comparison.

FHR Uses Existing NGNP Fuel Fabrication and Qualification Infrastructure

- FHR fuel operates at high power density and heavy metal loading, but lower temperature, than NGNP AGR fuel
- Rapid fuel testing is possible due to short time required for FHR fuel to reach full discharge burn up





Fuel Particle

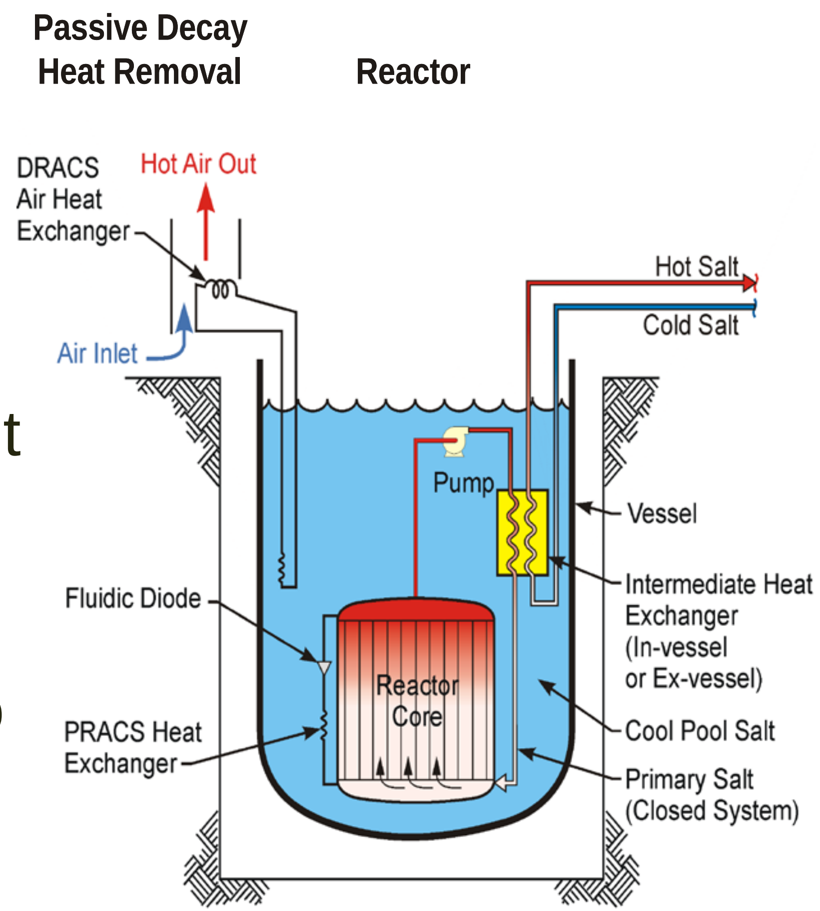
Current Modular FHR plant design is compact compared to LWRs and MHRs

Reactor Type	Reactor Power (MWe)	Reactor & Auxiliaries Volume (m^3/MWe)	Total Building Volume (m^3/MWe)
1970's PWR	1000	129	336
ABWR	1380	211	486
ESBWR	1550	132	343
EPR	1600	228	422
GT-MHR	286	388	412
PBMR	170	1015	1285
Modular FHR	**410**	**98**	**242**

Potentially Competitive Economics

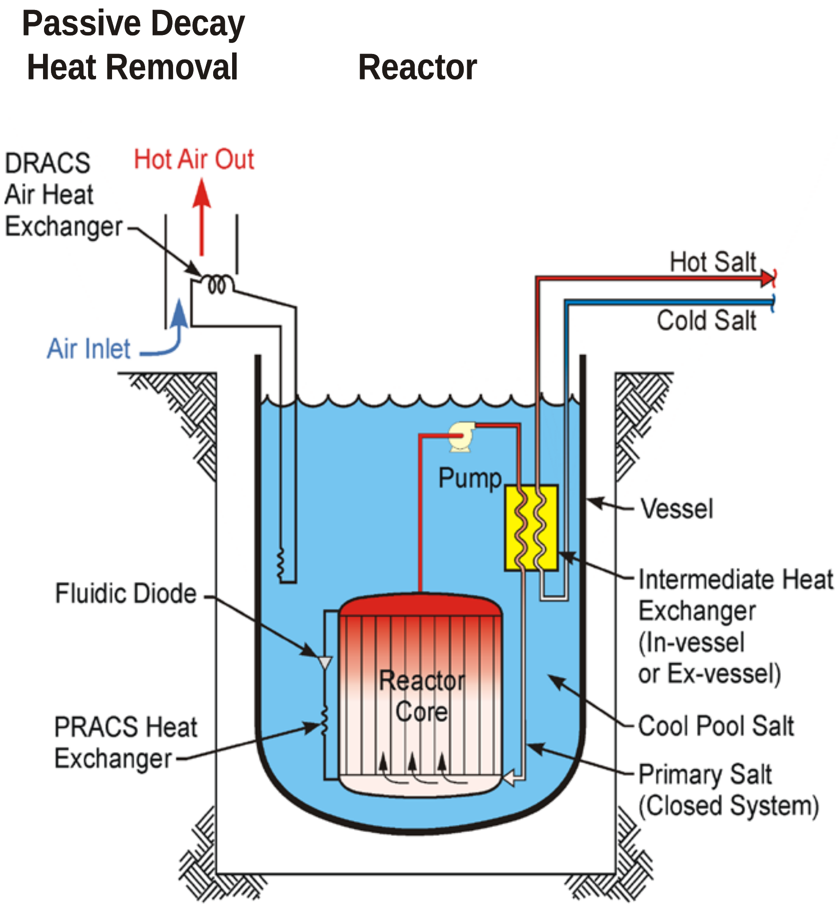
The FHR Primary System can be in a Secondary Tank Filled with Salt

- Secondary Tank Functions
  - Decay heat sink
  - Assure can not loose coolant under any conditions
  - Low surface area tank so do not freeze primary system salt piping when shut down
- Secondary Tank System
  - Soluble neutron absorbers so shut down reactor if leak
  - DRACS system to control secondary salt temperatures



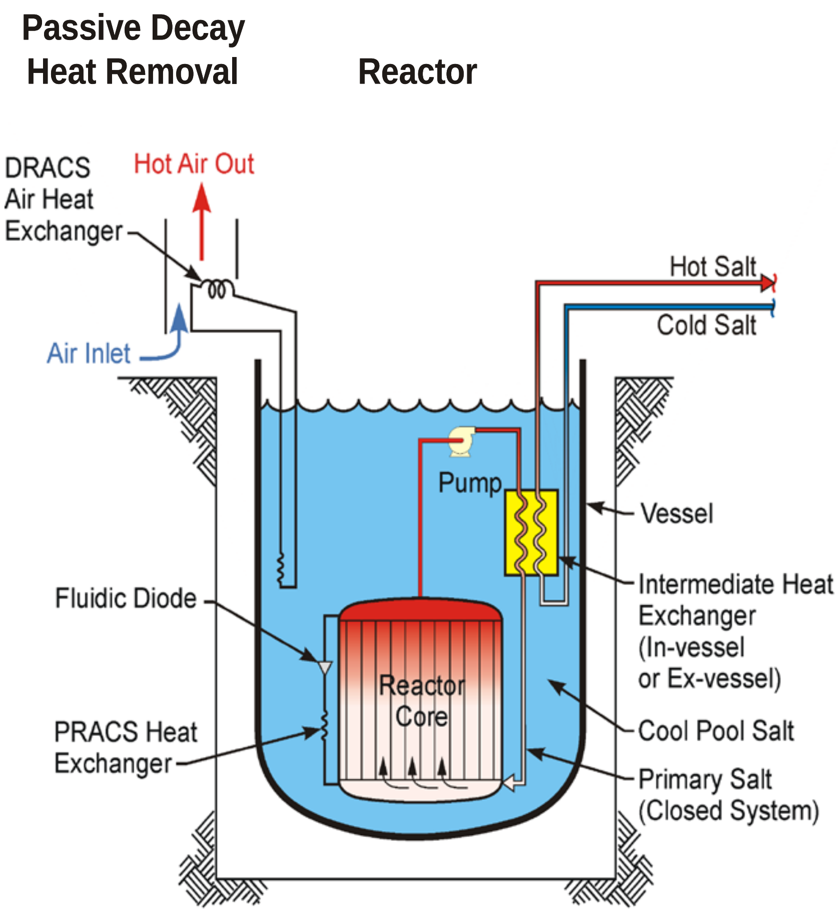
Decay Heat Dumped to Secondary Tank If Loose Primary Heat Sink (Power Cycle)

- Primary salt route
  - Reactor core
  - Primary heat exchanger to power cycle
  - Piping to reactor core
- Loss of heat sink to power cycle
  - Hot salt through HX
  - Hot salt to core through un-insulated piping
  - Dump heat to secondary salt at temperature of cold side of primary loop



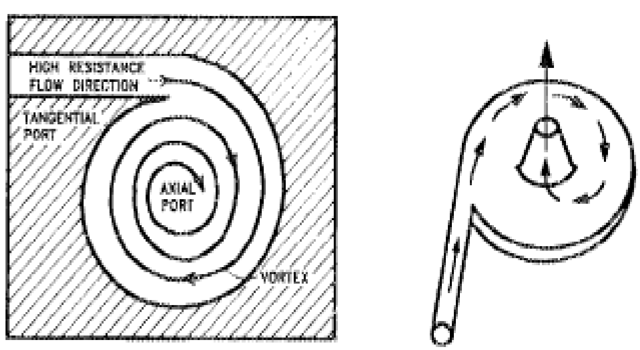
Decay Heat Dumped to Secondary Tank on Pump Trip

- Two routes for primary salt
  - Through reactor core
  - Through parallel PRACS heat exchanger that dumps heat to secondary salt
- PRACS loop
  - Heat exchanger and fluidic diode
  - High flow resistance when pump operates
  - If pump stops, salt flows through core and down PRACS loop



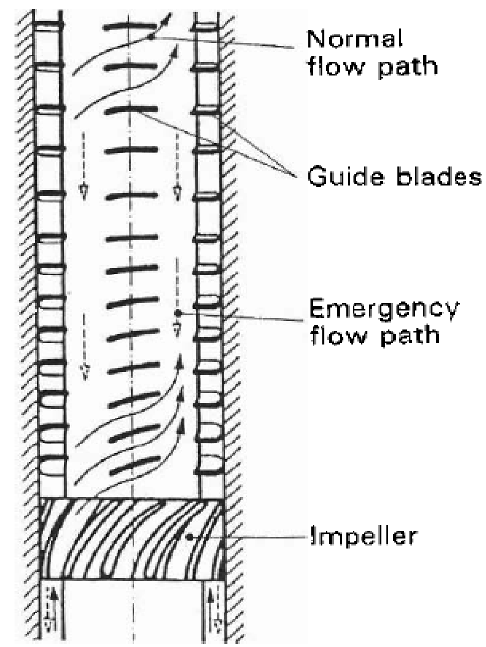
Fluidic Diodes Developed for German Fast Reactor and British Reprocessing Plants

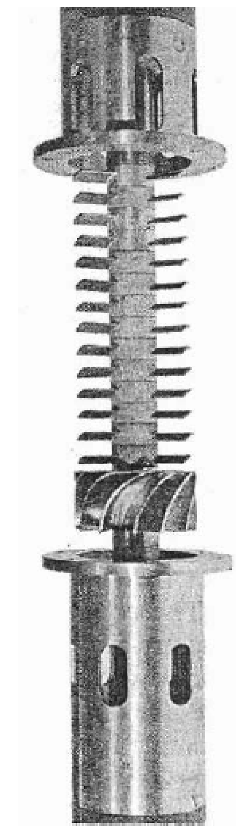
- No moving parts diodes exhibit anisotropic flow resistance
- Nuclear experience available
- Vortex diode chosen as target design (Large version used in MHI APWR and Korean AP-1400 Accumulators)



Conventional Vortex Diode

German fluidic diode for sodium (Fluid Rectifier Diode)

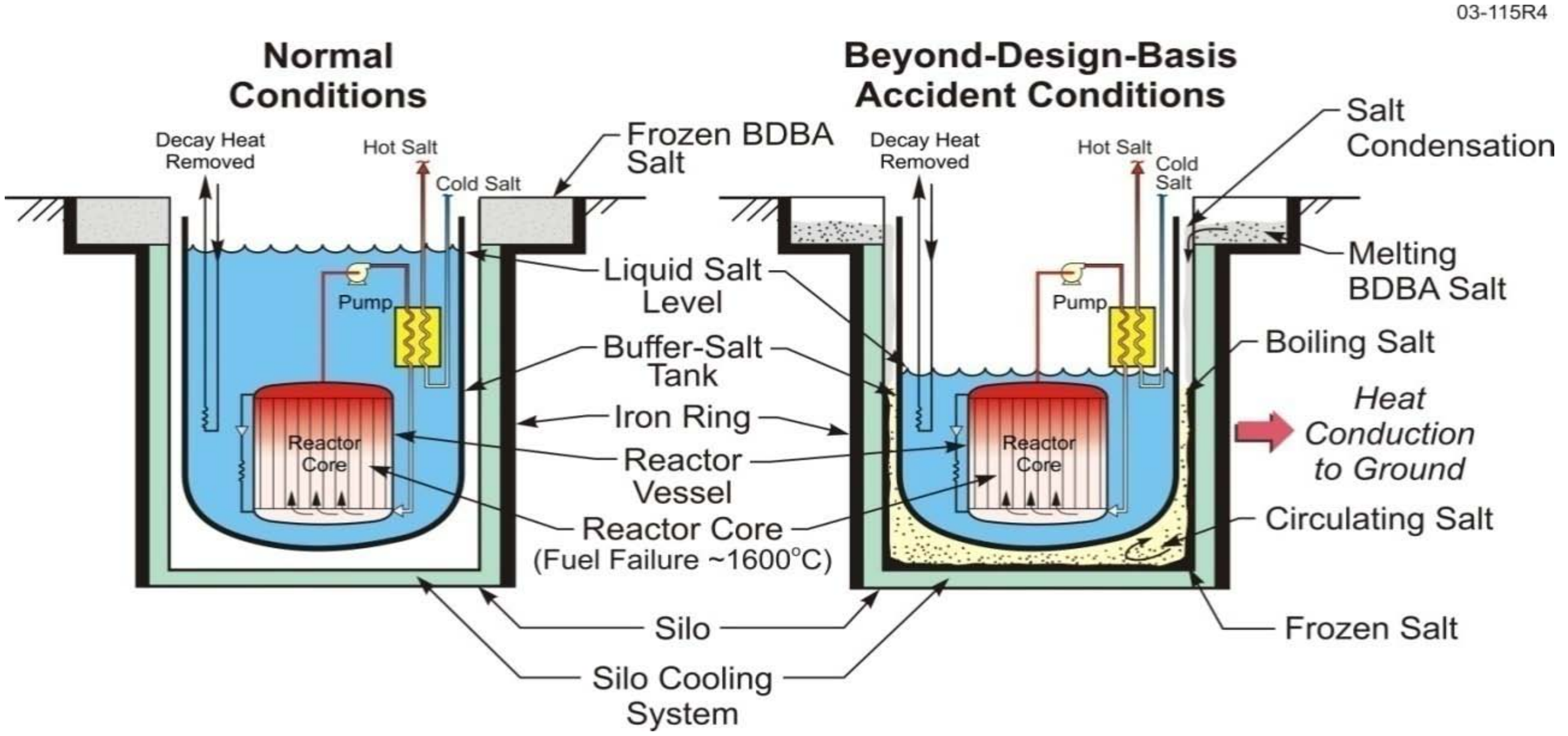




Rothfuss and F. Vogt, "Reactor Vessel Technology," *Nuclear Technology*, Vol. 78, pg. 245, 1987.

Potential for Large Reactor That Can Not Have a Catastrophic Accident

Large Temperature Drop to Conduct Heat To Ground



BDBA Salt Upon Melting Thermally Couples Reactor to Ground

FHR for Electricity

- Deliver heat from 600 to 700ºC
  - Lower temperature above salt melting point
  - Upper temperature within existing materials
- Power cycle options
  - Commercial supercritical water cycle with peak temperature of 650ºC
  - Supercritical carbon dioxide cycle with good temperature match between delivered heat and power cycle
  - Air Brayton cycle with good temperature match between delivered heat and power cycle

Exit Temperatures Meet Most Process Heat Requirements

- Initial version: 700°C
  - Use existing materials
- Refinery peak temperatures ~600°C (thermal crackers)
- Meet heavy oil, oil shale, oil sands and biorefinery process heat requirements
- Tritium control is an important design issue

FHR Core Design: 5 Shutdown Options

- Doppler reactor shutdown on high temperature
- Conventional control rod system
- Salt temperature-driven buoyancy control rods
  - Salt denser than graphite so can build near neutral buoyancy control rods
  - If salt heats up, salt density decreases, rods drop
  - If neutral buoyancy at operating temperature, hold up by fluid flow and drop on loss of flow
- Salt temperature-driven fusible link shutdown
  - Soluble neutron absorbers in canister (boron or rare earths) with nickel-gold fusible link (like fire sprinkler systems)
  - Overheat and release to hot salt
- Buffer tank absorber (Discussed later)

Salt-Fuel Combination Reduces Hot Spots in Reactor Core (Nominal Exit ~700°C)

Is an Accident in the Core Possible?

	Helium (Gas)	**Salt (Liquid) BP: 1430°C**
Pebble	Sinks in Helium	Floats In Salt
Fluid Flow	Down	Up: Pebbles Held in Place
Heat Transfer* with Temp. Increase	Viscosity Up; Flow Rate Down: Heat Transfer Down	Viscosity Down: Flow Rate Up; Heat Transfer Up
Margins	100°C?	>500°C

*Transparent High-Heat Capacity Salt With Radiation Heat Transfer ~ T^4

Status of FHR

- No FHR has ever been built: new concept
- On paper a great idea but untested concept
- Combines four technologies with changes
  - Gas-cooled reactor coated-particle fuel—but at higher power densities and with salt coolant
  - Clean molten (liquid) salt reactor coolant—but previous experience in MSR with fuel dissolved in coolant: both with high melting point coolant
  - Fast reactor safety systems—but with a high melting-point coolant
  - Power cycles—but at 700 C